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ARMSTRONG LABORATORY

DEVELOPMENT OF A VENTILATED OFF-GASSING BOOTH FOR CHEMICAL AGENT EXPOSURE STUDIES

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Chemical Defense (CD) shelter procedures development and ensemble configuration research uses off-gassing booths to determine the amount of chemical agent vapor transported by personnel into shelters and to quantify the exposure of individuals to agent vapors. A ventilated off-gassing booth (VOFGB) was designed, constructed and compared to the non-ventilated booths in use at Air Force test and evaluation facilities to determine whether the VOFGB would make off-gassing assays more accurate reflections of actual exposure. Ventilated booths study results showed that the VOFGB provided more predictable and reproducible values with need for much shorter testing times. The static (non-ventilated) off-gassing booths could provide similar superior results but only certain carefully controlled conditions. Extensive evaluation of the VOFGB further showed that certain factors including the technique of simulant vapor generation and the ventilation rate for the booth effect test results. Sorption/desorption of simulant by booth materials had an impact on observed vapor half-lives and booth peak vapor concentration levels.

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INTRODUCTION

The primary objective of this research was to develop a ventilated off-gassing booth (VOFGB) to test don/doff Chemical Warfare Defense (CWD) protective ensemble combinations. A second objective was to design and build structural additions to the Chemical Defense Research Facility,(building 1192) located on Brooks Air Force Base. Facility improvements were needed: a laboratory to fit test CWD protective masks, a dressing and briefing room for don/doff test subjects, and storage areas to stockpile protective equipment and supplies used for don/doff testing. The design and construction of the laboratory and research subject assembly areas in building 1192 are described elsewhere and require no further documentation. This report is concerned mainly with construction and comparison evaluation of the VOFGB.

VENTILATED OFF-GASSING BOOTH DEVELOPMENT

Investigations were conducted by the Armstrong Laboratory Crew Technology Division to isolate and measure CW agent simulant vapor off-gassed from "contaminated" test subjects and their clothing assemblies during shelter don/doff trials in sealed off-gassing booths. In these booths, simulant vapor concentration within the booth is continuously sampled and quantified. The only air removed from the booth was the sample volume which was replaced with clean air of the same volume. It was considered that better data might be obtained with a ventilated off-gassing booth that continuously exchanged clean air for booth air. British workers did preliminary research in this area but used a wood-and-plastic portable model. Mr. Robert Simpson, a former British civil servant, and now an Air Force contract employee, was familiar with the version used by the British. He was the author of the concept on which the VOFGB was based.

In the VOFGB, a metered flow of filtered air would continuously wash up through the booth past and around the test subject seated in the booth. This airflow would then exhaust from a duct at the booth's apex. Vapor sampling of the exhausted air was done in the duct. This approach provided booth vapor concentration data which could be equated to booth volumetric airflow and time, thus permitting estimation of total off-gassed simulant mass (excluding deposition/absorption losses) and rates of simulant mass flow.

The following sections outline the detailed design and technical requirements met in constructing the VOFGB. The final section presents initial study data to determine the amount of

simulant that could be recovered from the VOFGB. Where reference is made to "existing booths" it relates to the sealed/ unventilated booths previously manufactured for the Crew Technology Division from which many of the basic design requirements were derived.

CONSTRUCTION MATERIALS

The over-riding requirement for all internal surfaces of the booth and any ancillary fittings which would be exposed during experiments was resistance methylsalicylate (MeS) absorption. Materials used for the construction of the booth were identical to those used for the construction of the existing booths, i.e., glass, stainless steel, and Viton seals. The use of any sealing compounds in booth construction which were likely to release solvents to the booth under laboratory environmental and test conditions was avoided.

LEAK TIGHTNESS

During testing, it is essential that there is no mixing of filtered booth air with the local external environment (e.g., outside air leaking into the booth), and that there is no loss of filtered booth air except through the booth's exhaust duct. The contractor, Rothe Development, Inc., verified these conditions after construction.

GENERAL CONSTRUCTION AND DESIGN

General construction methods followed techniques adopted during manufacture of the existing booths, except for changes dictated by specific design or performance requirements. The booth, designed and constructed at a cost of $17,000, has a volume of 1697.4 L.

The shape of the booth is frustro-pyramidal, with a rectangular base, surmounted by a rectangular section and an upper pyramidal section, more sharply angled, which terminates at the apex with a vertical, cylindrical air-exhaust duct.

The frustro-pyramidal section was designed to accommodate a comfortably-seated occupant (Fig 1). One of the pyramid faces was a stainless steel and glass access door that permitted easy and unimpeded access to the interior. The remaining three sides were constructed of fixed panels of transparent toughened glass with stainless steel reinforcing corners. Glass and stainless steel were chosen for three reasons: structural integrity, resistance to MeS absorption (the test simulant), and subject observation.

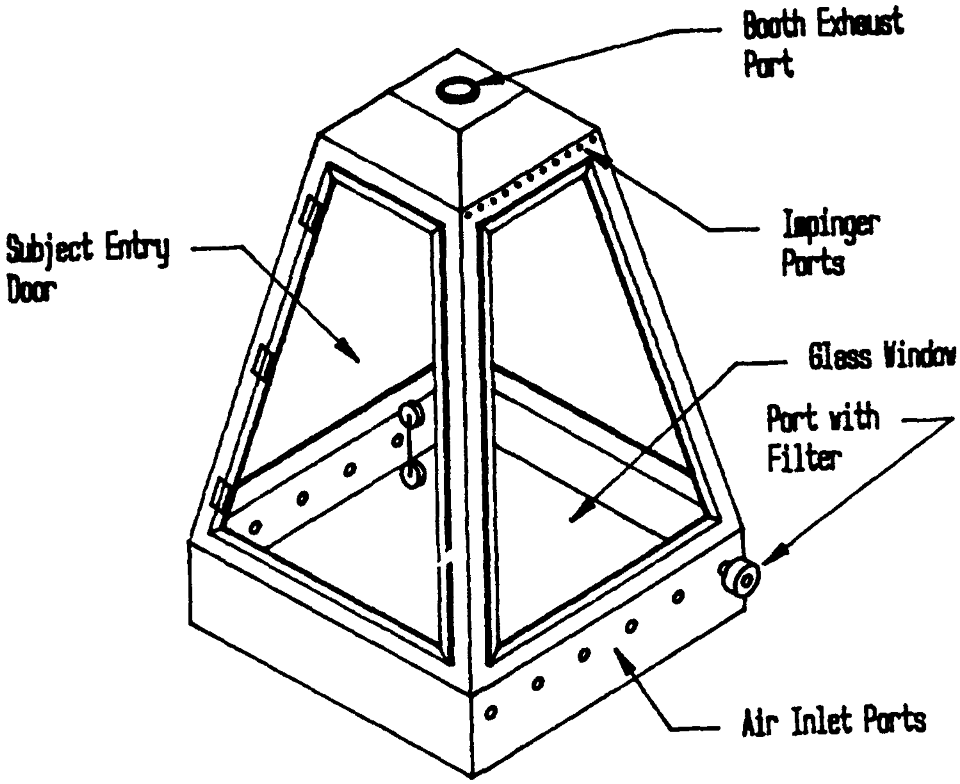

Figure 1. Ventilated offgassing booth.

The upper rectangular and pyramidal sections of the booth were constructed of stainless steel. The basic frame upon which the booth was constructed, the door and the door frame, are rigid and distortion free. A gas-tight seal between the access door and the door frame (Fig 2) prevents air from leaking into the booth.

The booth door has a cam-action latch which, in an emergency, could be readily operated from either inside or outside the booth. The design and location of the floor air-entry points took into account the positioning of the subject chair supports and the necessary post-test cleaning of the booth interior. A filter/ blower system supplies filtered air to the booth interior (Fig 3). The system airflow range is between 30 and 500 liters per minute (LPM), measured at the booth apex duct outlet. The method of flow control was flow by-pass; any flow within the stipulated range can be set and accurately maintained for periods of up to 5 hr.

The booth air filtration system has 12 standard chemical warfare filter canisters (C2 canisters) or their equivalent (Fig 4). "Life expired" canisters may be replaced without a major disturbance of the filter/blower system. The offgassing booth airflow moves through the CW filters and the booth pulled by a Rotron DR 101 Regenerative Blower; a suction bypass valve regulates air flow to any level between 0 and 500 LPM. An adjustable pressure relief valve can be set to open at a pressure of 2-6 in. of water as a safety feature to prevent the differential pressure

of water as a safety feature to prevent the differential pressure of the booth from exceeding the setting of the relief valve.

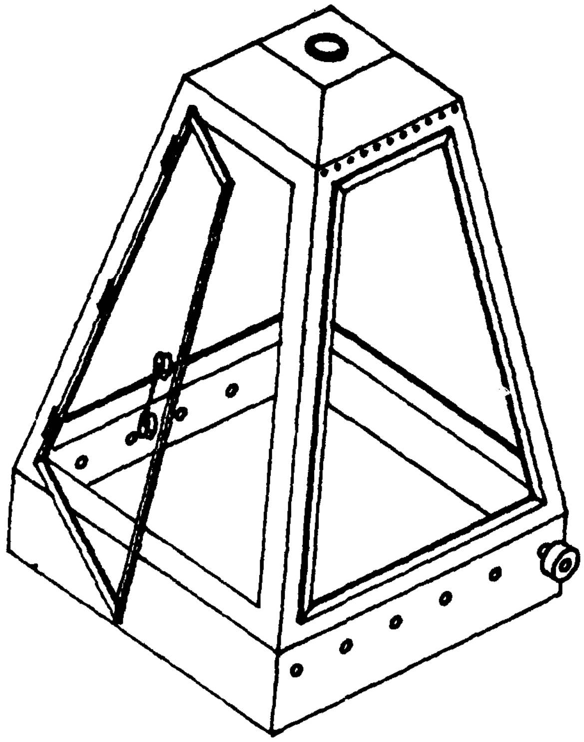

Figure 2. VOFGB with door open.

An airflow measuring device installed in the exhaust duct. is readily visible to personnel positioned outside the booth (Fig 5). The rectangular upper sections of the booth accommodated ports for 32 stainless steel bulk-head fittings connected to glass impinger samplers via 2.0-in. lengths of Tygon tubing (Fig 6). A holder for temporarily securing the impinger samplers was also installed within the upper section of the booth. The dimensions of the upper booth were purposely generous to accommodate and provide access to the 32 impinger samplers. Fabric test samples or military clothing test samples could be hung centrally within the booth.

The impingers are connected to a USAFSAM-developed* sampling pump by Tygon tubing (Figs 7 and 8). A pair of mixing fans set on the floor ensure good air movement inside the booth (Fig 9).

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*The Crew Technology Division was previously assigned to the USAF School of Aerospace Medicine (USAFSAM).

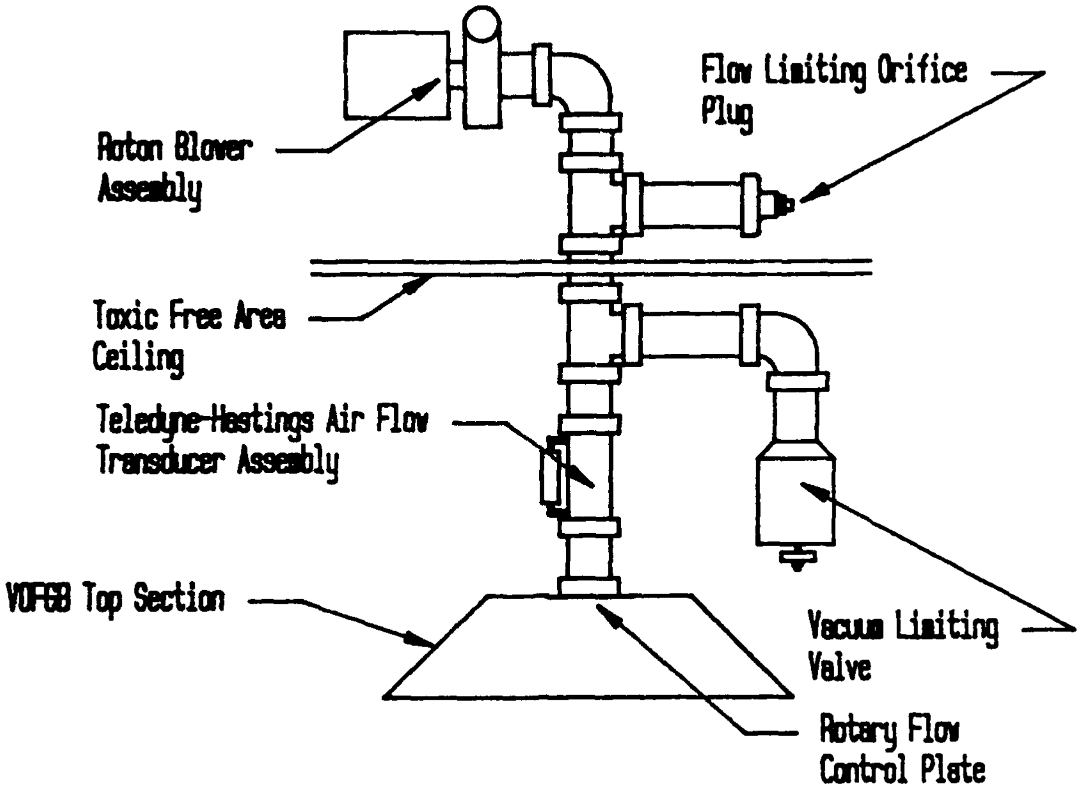

Figure 3. VOFGB air handling system.

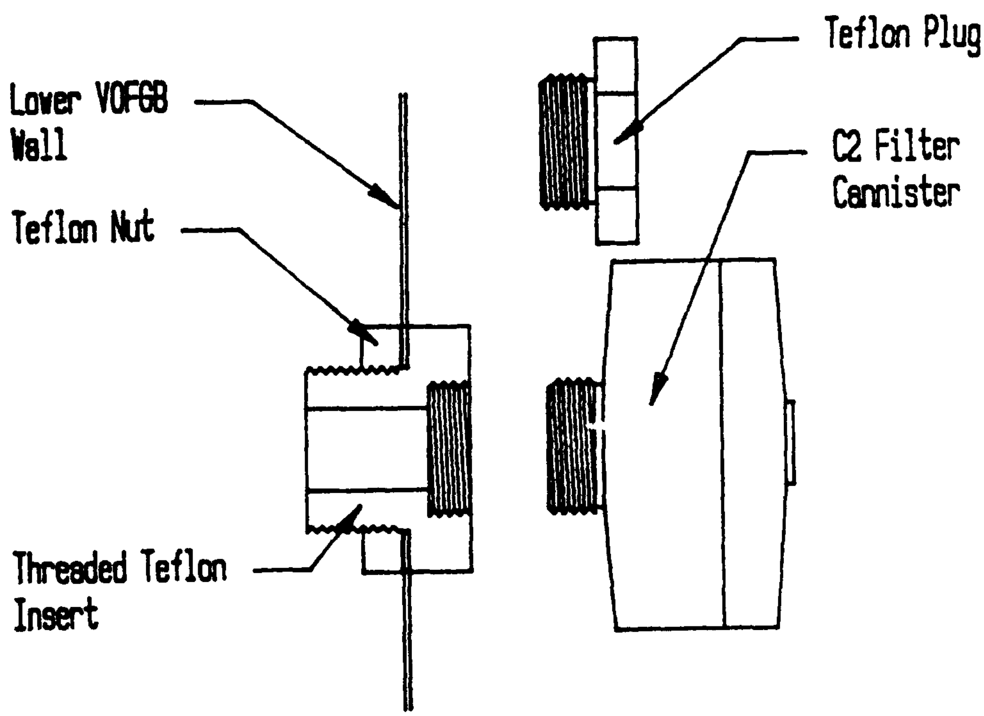

Figure 4. Air filtration canisters.

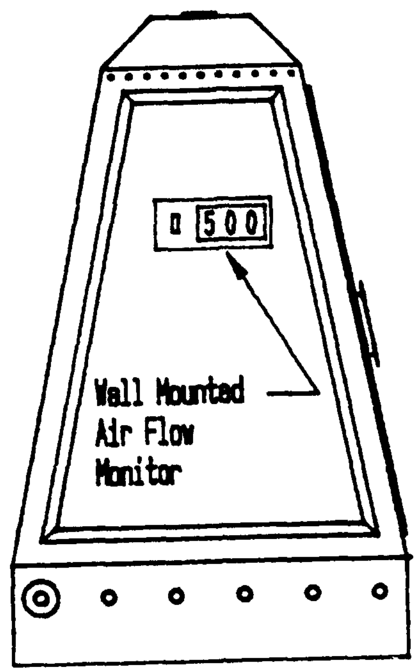

Figure 5. Air flow monitor.

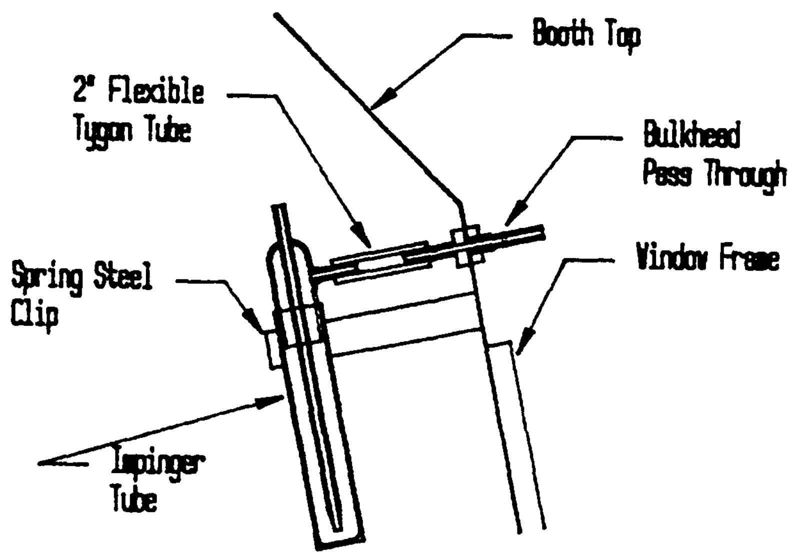

Figure 6. Impinger holding clips (Booth Upper Section).

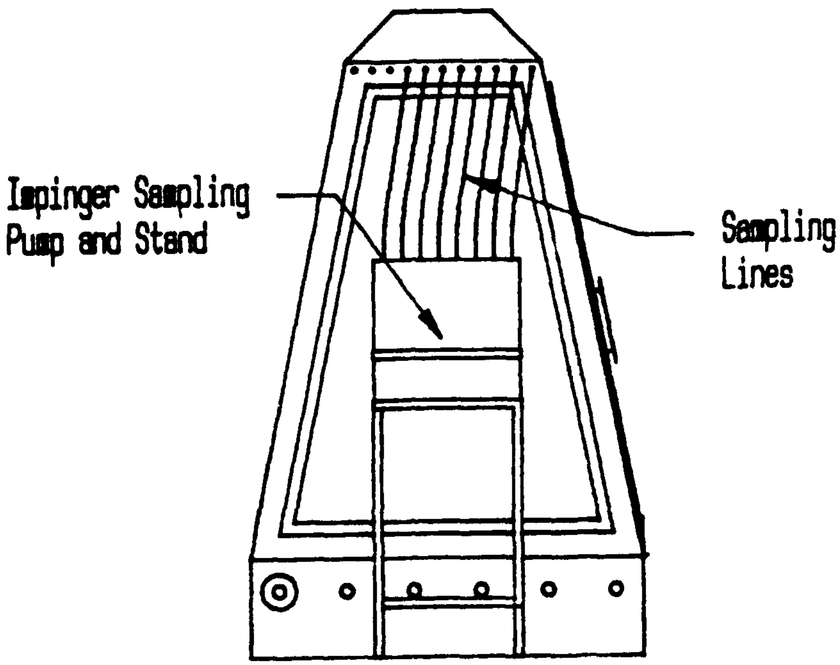

Figure 7. Side view of VOFGB showing sampling lines.

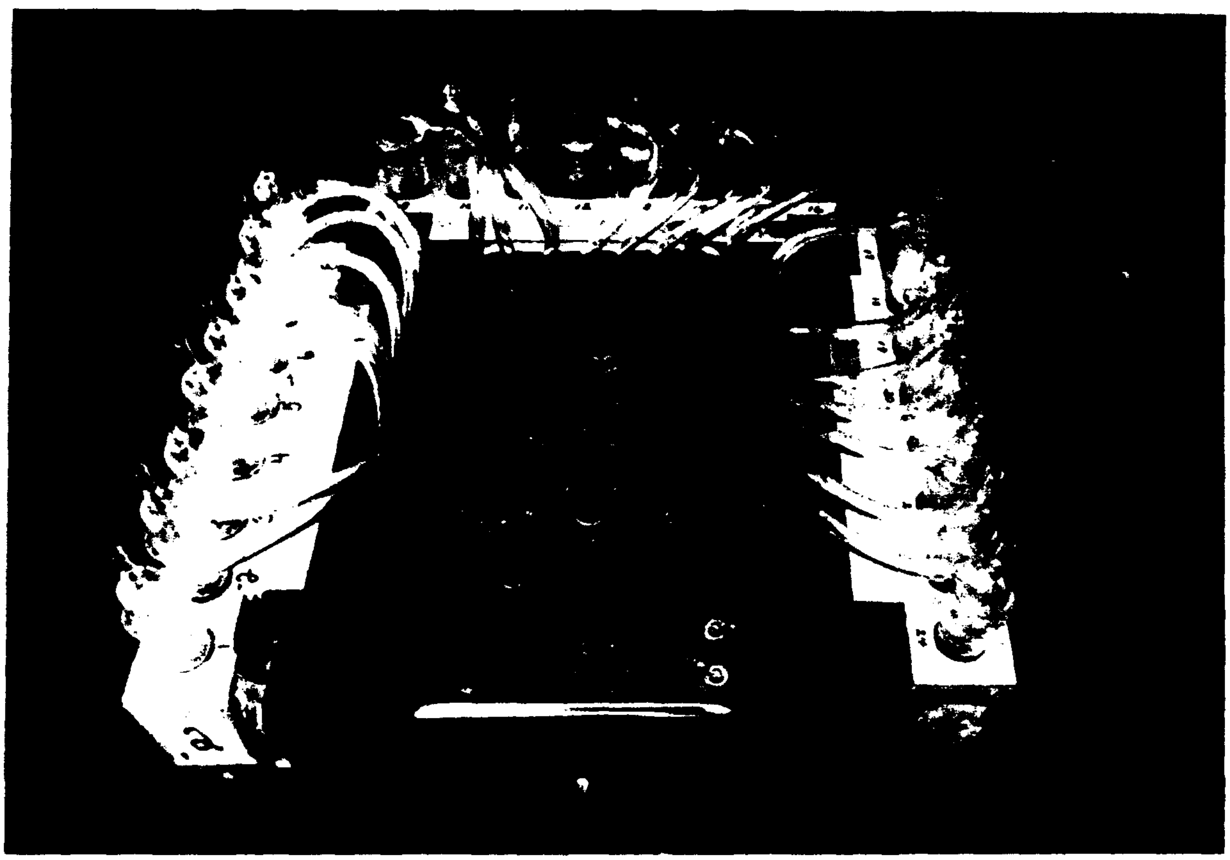

Figure 8. Impinger sampling pump.

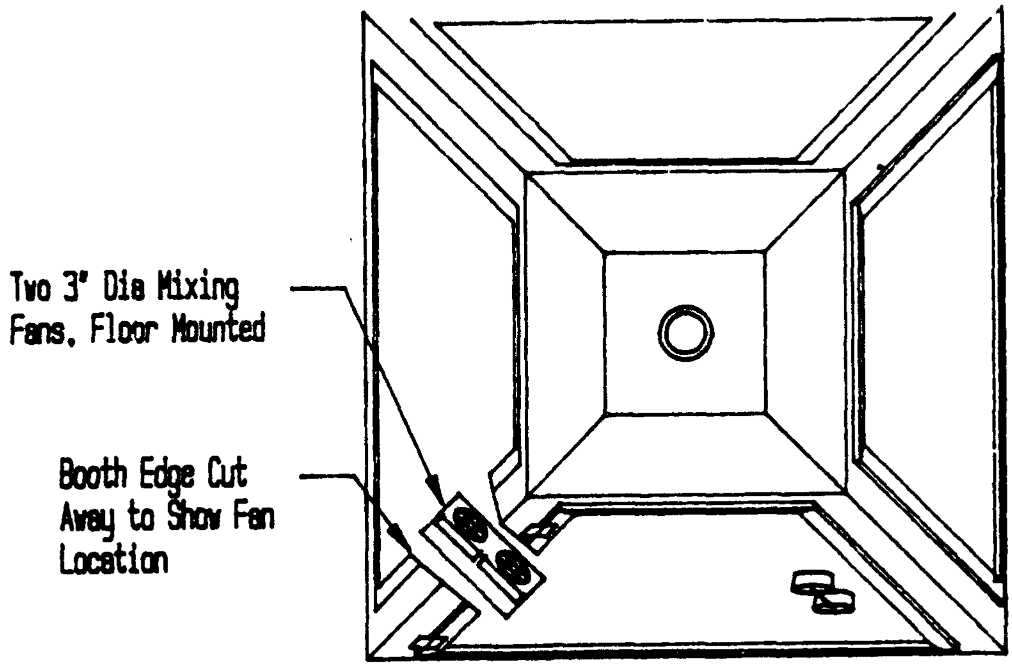

Figure 9. VOFGB mixing fans.

TESTING

Preliminary tests were conducted to determine the amount of simulant that could be recovered (introduced versus measured) using the ventilated booth. Carbon monoxide (CO) washout testing of the booths was also conducted at the start of the evaluation. Several different types of tests were then conducted, examining different facets of booth operation. The first comparison studies investigated offgassing of slides at ambient temperature and at elevated temperatures. In the final stages of preliminary testing, several ventilation rates were used with the VOFGB. Recovery values were compared with the unventilated booths. Performance of the unventilated booths were similar to each other; therefore, further comparisons required only one of the unventilated booths, (Booth 1 was chosen for all further tests.). Washout time for the unventilated booth determined a CO washout half-life of 3000 min (50 hours), much longer than the normal off-gassing periods used during typical don/doff testing. The half-life for the VOFGB was dependent upon the ventilation rate used -- evaluation was done using two ventilation rates, 53 and 107 LPM.

Results of CO washout at these two rates were log-linear, conforming to theory. CO half-life at 53 LPM was 22.1 min, and at 107 LPM was 11.0 min. For the off-gassing tests, MeS was applied to glass slides. The rate of evaporation is controlled by temperature. In different portions of the testing the slides were: left at room temperature (natural evaporation) or were heated to one of two temperatures by placing the slide on top of a beaker

heating sleeve (Fig 10). The two temperatures were either warm (approximately 100 degrees Fahrenheit) or hot (approximately 150 degrees Fahrenheit).

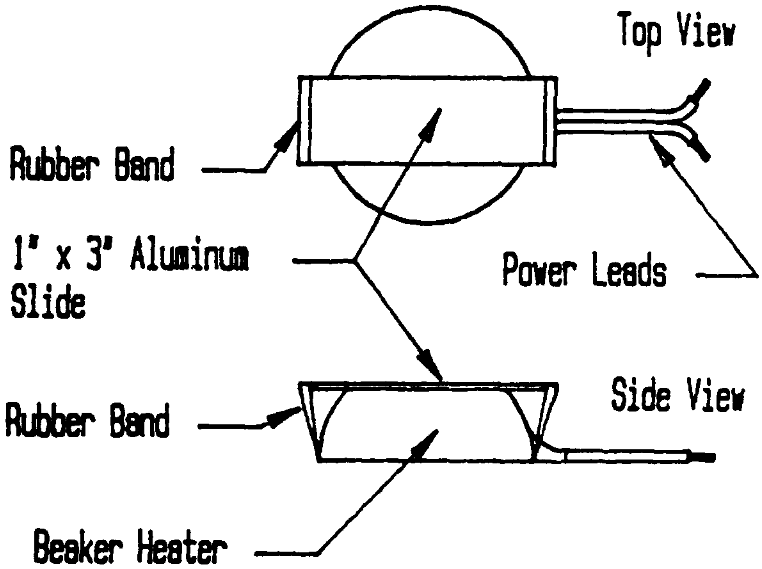

Figure 10. Slide heating apparatus.

One test compared the effects of heating the slide to the two different temperatures using the same booth ventilation rate (320 LPM). Four micrograms of MeS were used. Booth concentration at the higher level peaked at 1.8 $^{mg/m^{-3}}$ in 4 min. Within 30 min, 95.8% of the MeS had been accounted for. At the lower temperature, the peak booth concentration was 0.5 mg/m^{-3} which occurred around 25 min. About 87.4 % of the MeS had been accounted for within 45 min (Fig. 11).

A second series of tests examined the effects of ventilation rate on the vapor concentration half-life and on MeS accountability. Each point in the figures represents a minimum of three samples. Four different ventilation rates were used. Different amounts of MeS were used for each ventilation rate, but the amount used for any one ventilation rate was constant. Ten 5-min impinger samples were collected for each condition. Increasing the ventilation rate had the effect of increasing the percentage of MeS accounted for within the 50-min period. At 54.8 LPM, accountability was 70%; it increased to 83.8% at 101 LPM, 95.6% at 150.5 LPM, and 100% at 201.3 LPM. In each case the estimated total accountability of MeS would have been greater than 90% if the test had been allowed to run to completion. These quantities were estimated by using a composite half-life from the last four sets of samples and extrapolating the concentrations to zero. The standard

deviations noted for the repetitions are all small and are within acceptable limits.

Similar amounts of MeS may be accounted for in the unventilated booths, using a testing period approximately five times that needed for the VOFGB. Given a limited number of available sampling ports, the sample period must be increased.

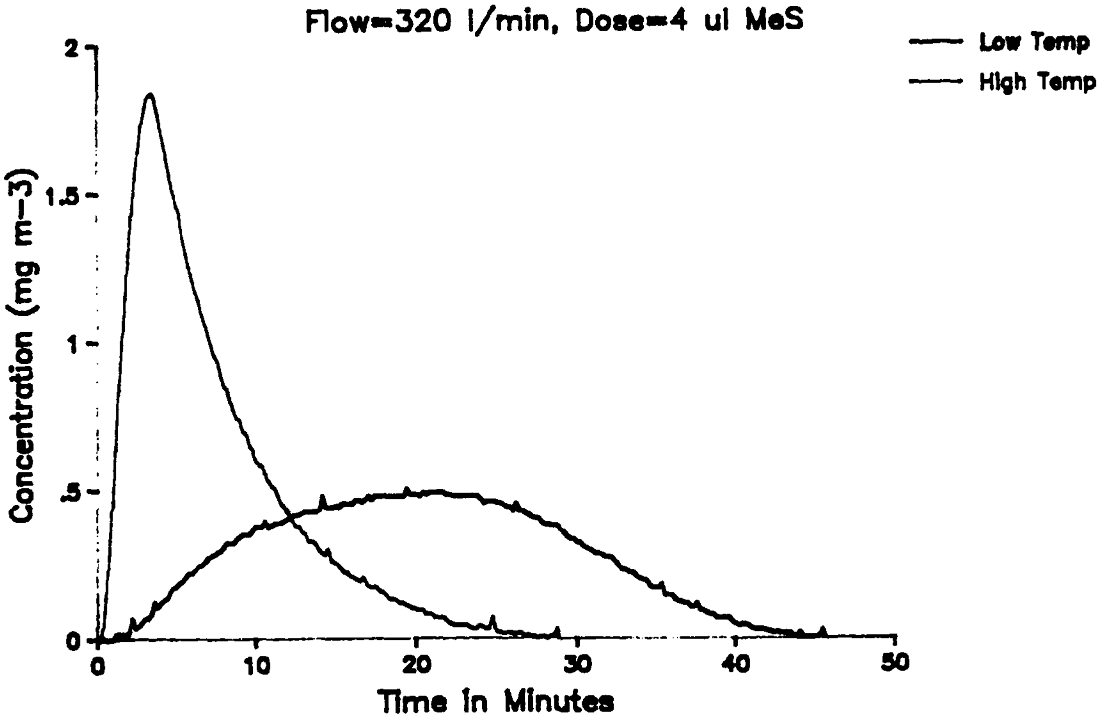

Figure 11. VOFGB simulant levels for 4 µl of MeS generated at two different temperatures.

DISCUSSION

The general equation that describes vapor concentration in a volume with ideal dilution ventilation once the source of contamination is removed is:

$C=C_o e^{-\_t}$

where,

C = Concentration in µg l^{-1}
C_o = Initial concentration in µg l^{-1}
t = Time in minutes
_ = *A constant related to vapor half-life*
e = 2.718282, the natural logarithm base.

Carbon monoxide (CO) was used as a non-reactive gas (with respect to off-gassing booth materials) to estimate ventilated off-gassing booth (VOFGB) washout characteristics. The CO concentration in the VOFGB was initialized by adding pure CO until a stable concentration of about 200 ppm was reached. The source of CO was shut off and VOFGB CO concentration was monitored during decay through about one concentration decade (200-20 parts per million (ppm)). Figures 12 & 13 represent the testing results. The linear regression line calculated using the natural log of CO concentration vs time formed a nearly perfect exponential (R^2=.99+). At the low flow rate (53 LPM), the CO half-life within the VOFGB was about 23.9 min compared to a calculated ideal half-life of 22.2 min. At the high flow rate (107 LPM), the measured CO half-life was 11.11 min compared to a calculated ideal half-life of 10.99 min. The difference between these two results probably indicates that, as flow increases, better mixing occurs within the booth bringing actual conditions closer to those assumed as ideal dilution ventilation conditions. Even for the low flow condition, the departure of actual from ideal dilution was only about 8%.

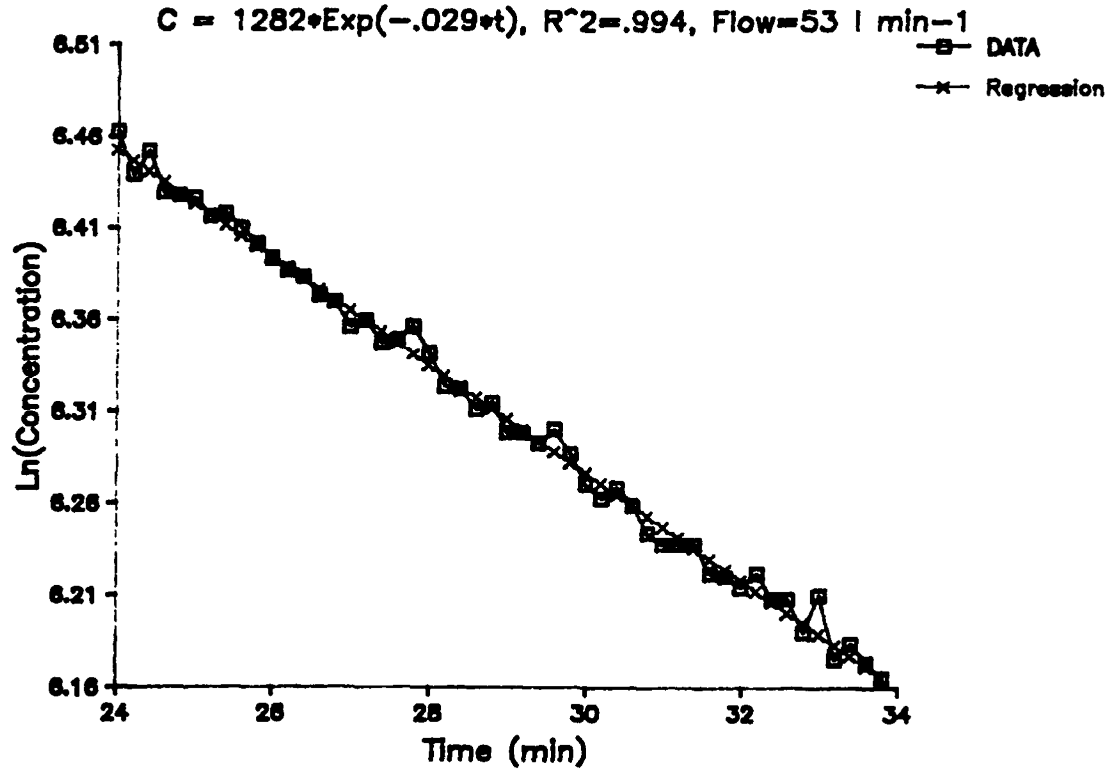

Figure 12. VOFGB CO washout, 107 LPM ventilation.

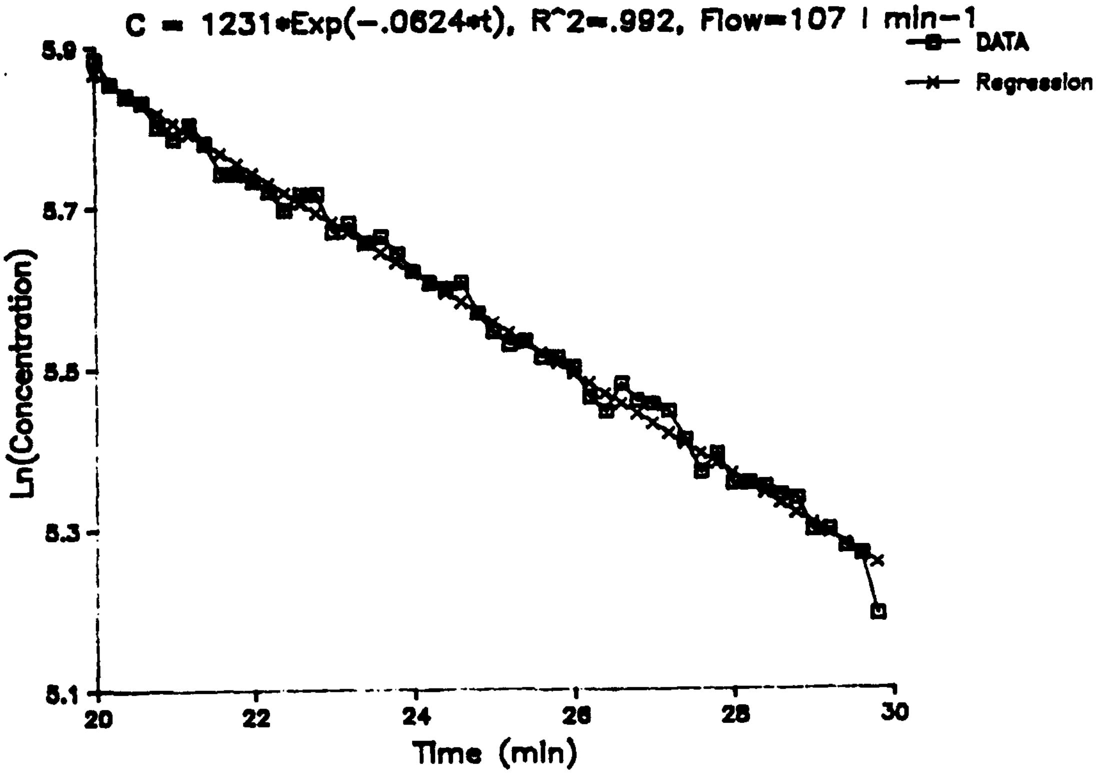

Figure 13. VOFGB CO washout, 53 LPM ventilation.

MeS, the primary chemical agent simulant used at the Brooks AFB facility, simulant has physical properties that are very similar to those of the chemical agent, distilled mustard (HD); it is by no means a non-reactive perfect gas, which leads to some interesting observations with respect to how MeS responds in the offgassing booth environment. All of the MeS vapor recovery experiments were set up by placing a known amount of MeS on a slide within the off-gassing booth. These slides were tested at either room temperature (natural evaporation) or at an elevated temperature (heated). The MeS concentration-time curves within the VOFGB were determined at several ventilation levels (three replicates at each level). Figures 14 through 17 present the heated slide build-up and decay of concentration at various flushing flow rates within the VOFGB. Figure 18 presents an average vapor concentration (n=3) during the natural evaporation of MeS within the VOFGB. Please note that the time it took for the vapor level in the natural evaporation mode (Fig. 18) to reach peak concentration was longer than the elapsed time for an entire heated

run at a similar ventilation level (Fig. 14). When working with a dynamic system such as the VOFGB, many different reactions may occur simultaneously, each driven by a separate rate constant. For example, the rate of change of simulant concentration in the VOFGB probably depends upon slide temperature and simulant physical characteristics (evolution rate), simulant extinction rate, booth inner surfaces sorption/desorption rate and booth ventilation rate. In equation form, the change in the quantity of simulant (_Q in µg) in the booth during time interval _t would look like:

$$\_Q=\_Q_r+\_Q_{sd}-\_Q_e-\_Q_v \qquad [1]$$

Where,

$\_Q_r$ = Mass of vapor (µg) generated during time _t,

$\_Q_{sd}$ = Mass of vapor (µg) sorbed or desorbed from VC walls during time _t,

$\_Q_e$ = Mass of vapor (µg) which reacts with air or booth materials,

$\_Q_v$ = Mass of vapor (µg) removed by ventilation during time _t.

Please note that $\_Q_{sd}$ can be either positive or negative (sorbed or desorbed). Following this equation, the simulant concentration in the VOFGB becomes at the end of each time element _t:

$$Q_t = \_\_Q_{0}^{t} \qquad [2]$$

$$= Q_t/V \qquad [3]$$

where Q_t is the summation of all _Qs up to time t, C is concentration (µg l^{-1}) in the VOFGB, and V is the booth volume (1697.4 L). All of these various vapor decay factors are potentially exponential in nature, similar to dilution ventilation.

If one or more of the above conditions are applicable, then VOFGB vapor concentration profiles should change when booth dynamic conditions change. These changes in vapor concentration profiles can be shown if you consider the vapor concentrations plotted in Figures 14 - 17 and the variations in the half-life of these vapor concentrations documented in Table 1. This table lists measured changes in effective vapor decay half-life as a function of time. A sliding four point linear regression of the natural log of vapor concentration vs time was used to determine the slope of the decay curve at selected times after peak booth concentration.

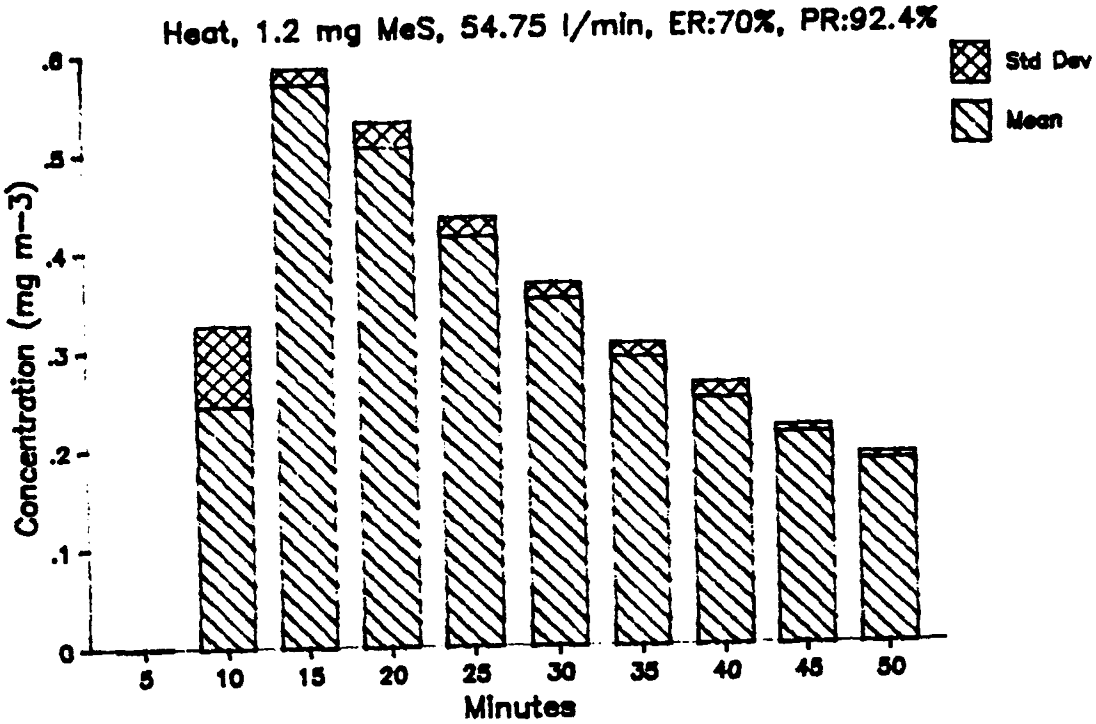

Figure 14. Composite VOFGB washout, 54.8 LPM ventilation.

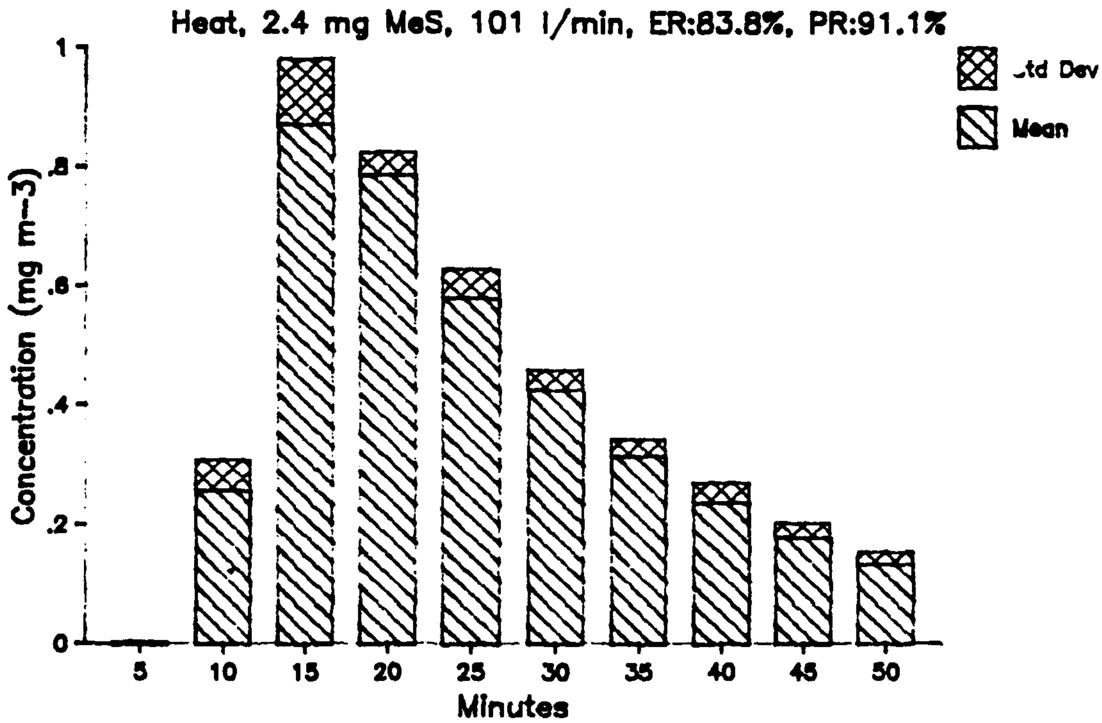

Figure 15. Composite VOFGB washout, 101 LPM ventilation.

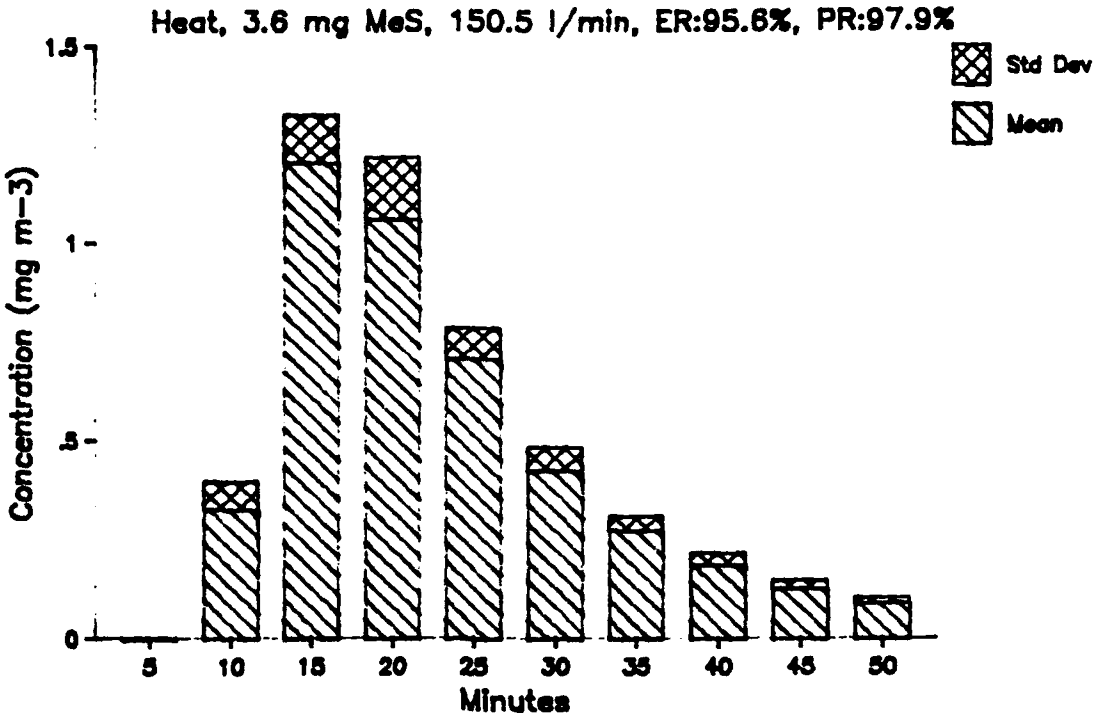

Figure 16. Composite VOFGB washout, 150.5 LPM ventilation.

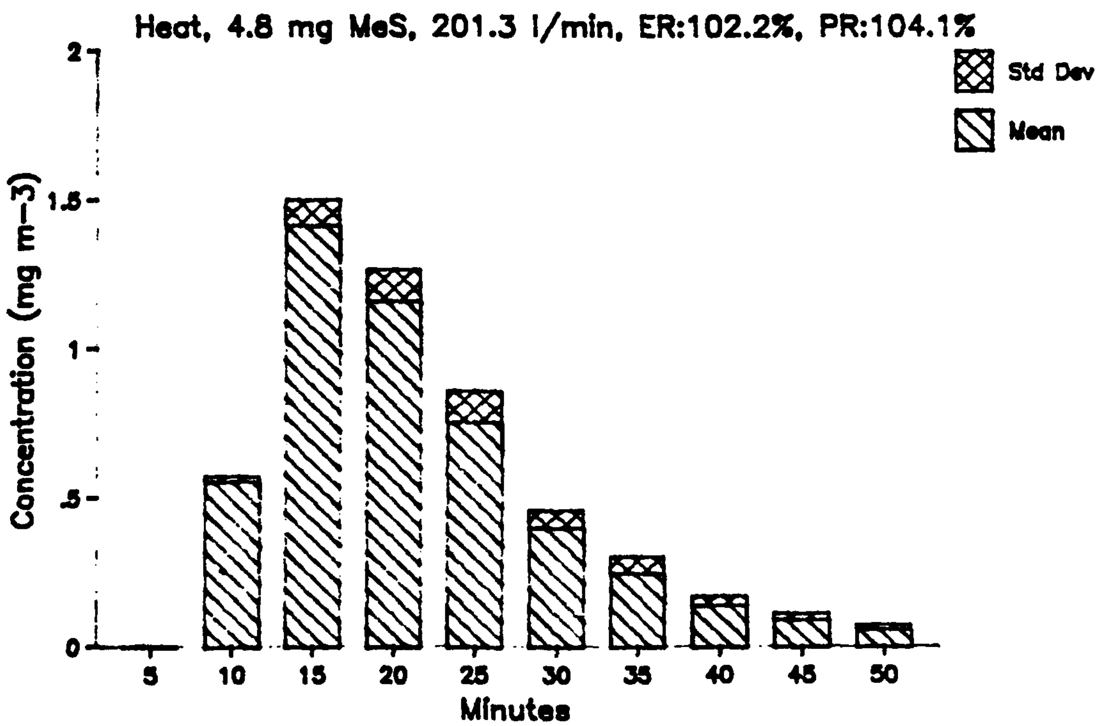

Figure 17. Composite VOFGB washout, 201.3 LPM ventilation.

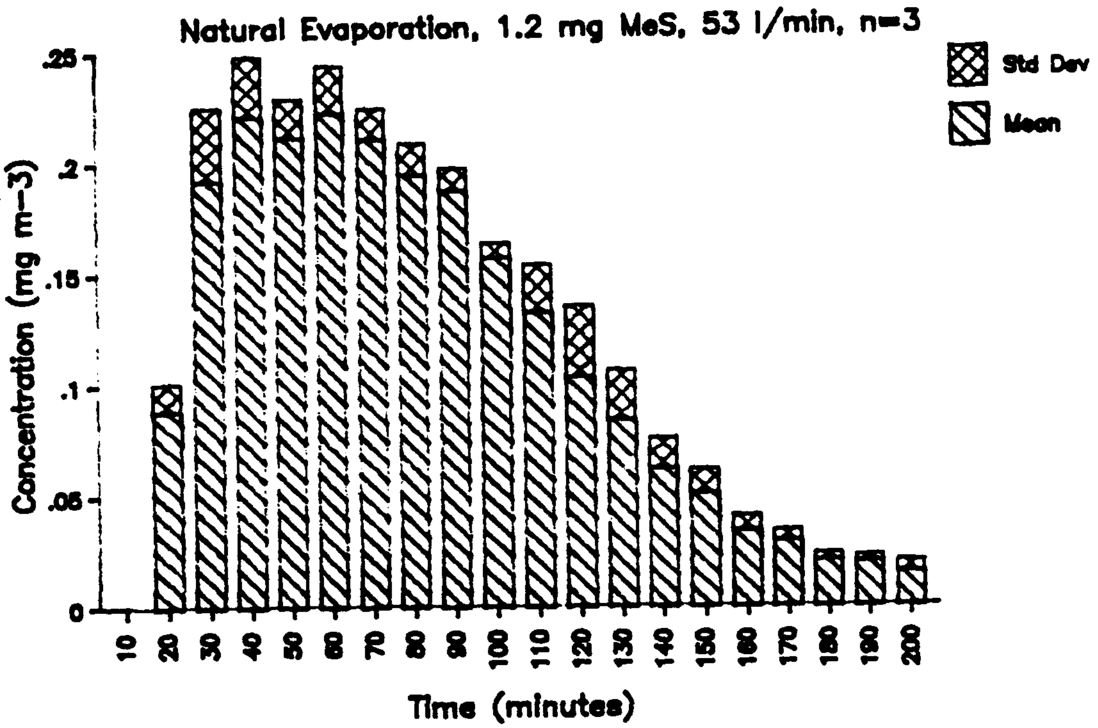

Figure 18. Average VOFGB washout for 1.2 mg Mes at 53 LPM ventilation.

TABLE 1. EFFECTIVE VAPOR HALF LIFE AT VARIOUS TIMES DURING VENTILATED BOOTH WASHOUT

Mid Time (min)	Booth Flow Rate (LPM)			
	54.75	101	150.5	201.3
22.5	21.01	14.07	9.79	8.2
27.5	18.94	11.33	7.55	6.57
32.5	20.08	11.65	7.79	6.26
37.5	20.85	11.99	8.64	6.96
42.5	22.84	12.21	9.26	7.35
Ideal t 1/2:	21.48	11.64	7.83	5.84

All four of these tests used the heated evaporation of the simulant MeS. The first three flow conditions (54.75, 101, and 150.3 LPM), produced minimum measured half lives shorter than the calculated ideal half-life. The high flow condition (201.3) produced a measured half-life greater than the calculated ideal half-life. All of the test conditions produced significant variations in half-life over the concentration decay time of each experiment. This change in effective half-life was not observed during CO testing using a similar set of VOFGB operating

parameters. The good fit of the regression lines in Figures 12 and 13 indicate that the concentration decay half-life of CO proceeded the same half-life for the entire concentration decay period. These findings indicate that factors other than dilution ventilation and vapor generation rate are significantly affecting the simulant vapor concentration profile within the VOFGB.

Referring back to eq.(1), $\_Q_e$ and _Qsd could both decrease the effective concentration decay half-life by removing simulant from the air within the booth. The $\_Q_{sd}$ term could also serve to lengthen half-life by desorbing simulant from the booth inner surfaces (during periods of low concentration) that was sorbed onto the inner surfaces during periods of high concentrations. The $\_Q_r$ term could initially lengthen the apparent half-life immediately post peak concentration but should go to zero and have no effect late in an experiment because all of the liquid has evaporated. The fairly high simulant accountability (91-100%) in the heated slide experiments indicates that the extinction term ($\_Q_e$) is probably not a significant contributor to the shorter than ideal vapor half-lives shown by the first three VOFGB test conditions. On the other hand, if the liquid has all evaporated ($\_Q_r$=0) and the vapor concentration is still high enough to cause sorption onto the booth inner surfaces, then a short-term reduced effective half-life (compared to the ideal dilution ventilation half-life) could result because both the $\_Q_{sd}$ and $\_Q_v$ factors would be negative, causing a quicker concentration decay. The increasing half-life observed in every case (Table 1) as a function of time is probably caused by simulant sorbed on the booth inner surfaces desorbing back into booth air which effectively lengthens contamination half-life. In the 201.3 LPM case (Table 1), the less than dilution ventilation half-life was not present because the high ventilation rate probably reduced the booth vapor concentration to desorption levels before all of the simulant had evaporated from the slide.

The final example of how different VOFGB booth conditions produce different vapor concentration profiles is given in Table 2. The flow condition of 53 LPM is similar to the 54.8 LPM (Table 1 and Fig. 18); however, the resulting effective half-lives are very different. The natural evaporation condition (Table 2 and Fig 19) runs much longer than the heated condition, 200 vs 50 min, and generates a vapor level peak much lower than the heated condition, .22 mg m^{-3} vs .56 mg m^{-3}. Unlike the heated slide condition the shortest measured half-life was considerably longer than the ideal dilution ventilation half life. The long period of time spent near peak simulant vapor levels provided time for inner surface sorption to approach equilibrium conditions; combined with a prolonged evaporation of simulant, it probably influenced the much longer effective half lives observed. As a final comment, the simulant accountability, still good with an average of 1188 µg accounted for out of 1205 µg applied at the end of the three test runs, indicates that the extinction term ($\_Q_e$) was not significant for the unoccupied ventilated off-gassing booth.

TABLE 2. CHANGING VOFGB VAPOR HALF-LIFE WITH NATURAL MES EVAPORATION

Mid Time	Half-Life
110	34.37
120	29.9
130	28.56
140	25.55
150	25.64
160	25.2
170	29.13

Ideal 1/2: 22.19
Flow: 53 l min^{-1}

In the static off-gassing booths, there was very little reduction in concentration with time when a non-reactive, near perfect gas (CO) was used to measure booth washout. Figure 20 provides the results of the CO tests for the static offgassing of booth #1 (OFGB1). The slope of the plotted line yields a calculated half-life of approximately 3300 min (55 h) which indicates that this off-gassing booth is nearly air tight. The static off-gassing booths have a volume of approximately 2613 L. During the MeS washout testing of unoccupied static booths, the sampling flow rate out of OFGB1 was 1.8 LPM. The sampling flow rate out of OFGB3 was 1.0 LPM. These two ventilation values yield ideal dilution ventilation half-lives of 1002 and 1803 min respectively.

Figure 20 shows the heated slide washout of OFGB1. Figure 21 gives the natural evaporation washout of OFGB3. Ten-min impinger air samples were collected from OFGB1. The 30-min impinger air samples used for OFGB2 allowed the simulant to evaporate at room temperature, but it slowed down booth response which required more total elapsed time to establish a characteristic vapor decay response pattern.

The reaction of the static booths to the change from a perfect gas (CO) to the simulant MeS was similar to that of the VOFGB. For a static booth, simulant accountability was calculated by multiplying the peak concentration (mg m^{-3}) times the booth volume (m^3). For heated evaporation, virtually 100% of the simulant added to the booth was accounted for. When the simulant was allowed to evaporate at room temperature, accountability was about 87%. The difference in simulant accountability probably results from the much longer time before peak (Figs 20 and 21) available for sorption to the booth inner surfaces (during room temperature evaporation) which effectively reduces peak concentration.

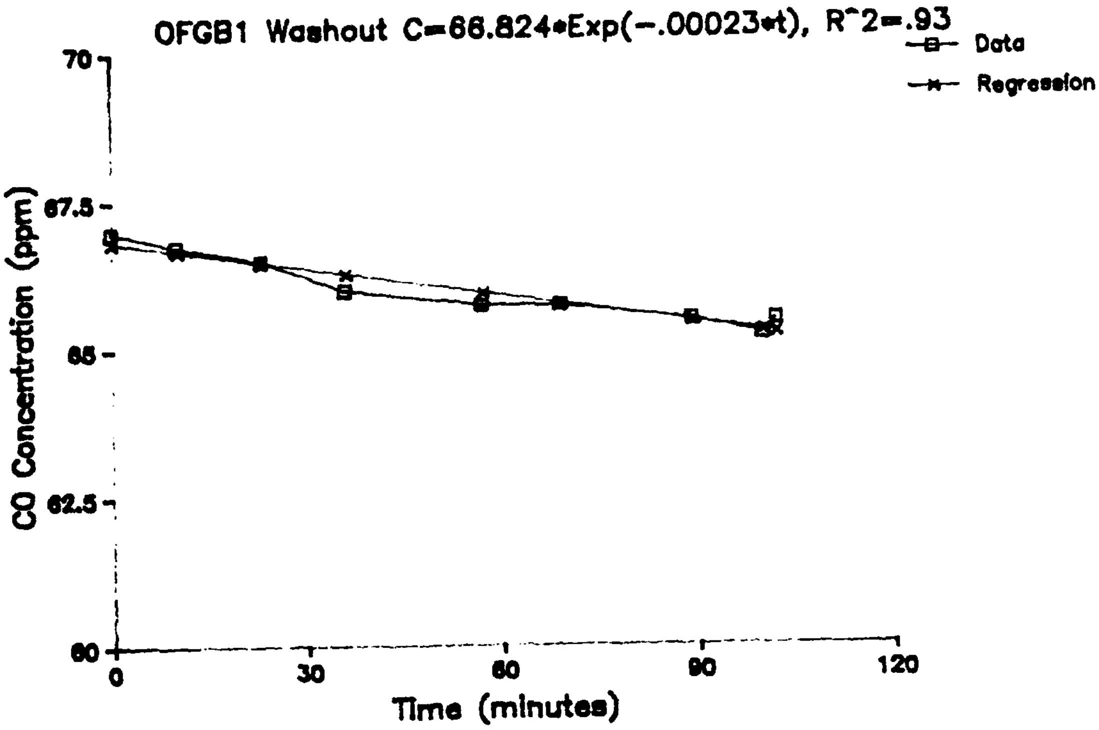

Figure 19. Static OFGB1 CO washout.

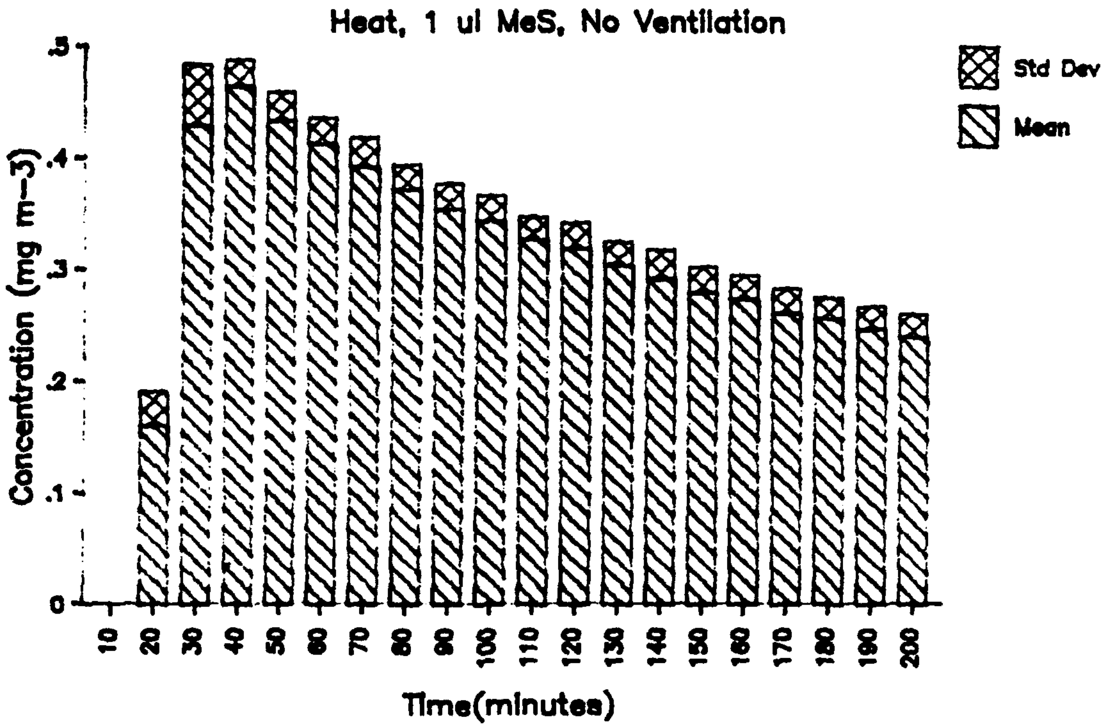

Figure 20. Static OFGB1 heated simulant vapor washout, n=4.

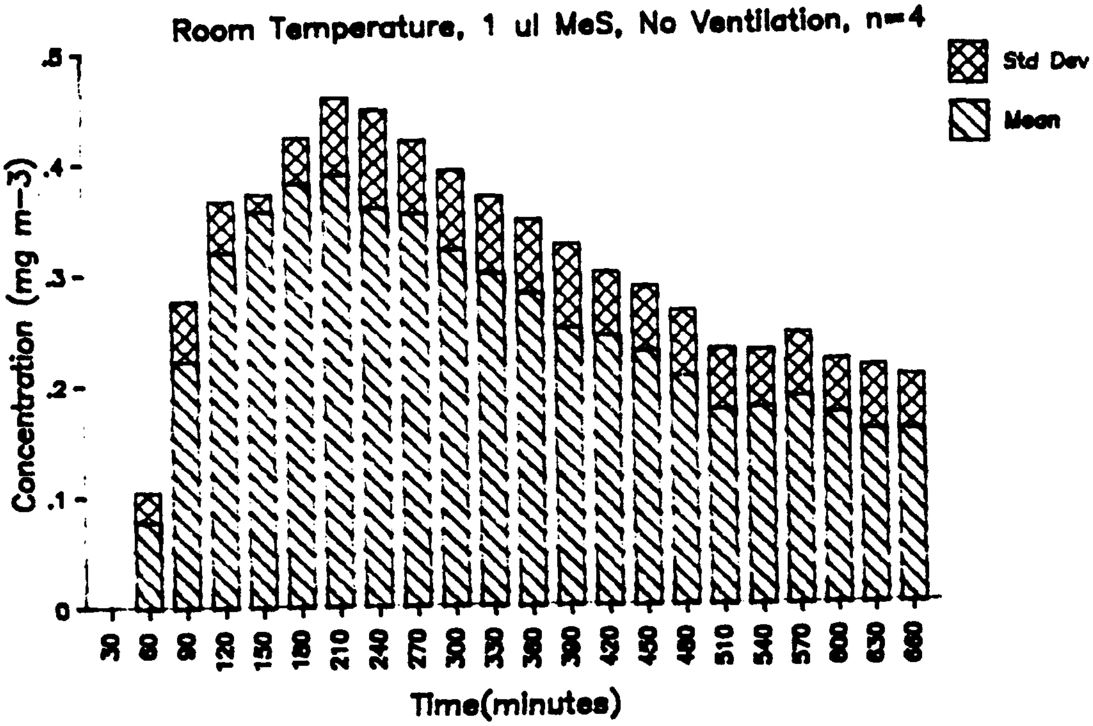

Figure 21. Static OFGB3 room temperature simulant vapor washout.

The variable half-life effect was also observed in static booth washout. Referring to Figures 22 and 23, the initial post peak half-lives were much shorter than dilution ventilation would predict (145 vs 1002 min. and 280 vs 1803 min). These times indicate that significant sorption of simulant onto booth inner surfaces continues for a considerable length of time after the booth is contaminated. As time progresses, the increasing half-lives indicate sorption is still taking place but at reduced rates. The measured vapor half-lives failed to approach the ideal dilution ventilation values because neither of these experiments was run long enough to allow sorption on booth inner surfaces to reach equilibrium.

The summation of simulant being exhausted from the VOFGB represents a true estimate of the amount of simulant offgassed into the VOFGB because the decreasing concentration in the booth causes the sorbed simulant to desorb from the inner surfaces and leave the booth. In the nonventilated booths, the relation between off-gassed simulant and the quantity of simulant carried in was not as predictable. Factors such as booth temperature and who or what is occupying the booth can have a pronounced effect on peak simulant concentration. Empty booth simulant accountability (peak*volume) with room temperature evaporation can be as high as the 87% reported in this effort. However, simulant accountability can drop to less than 50% for selected subjects with room temperature evaporation (2). Simulant recovery calculated from peak off-

gassing concentrations is, at best, a highly variable estimate of the amount of simulant carried into a static off-gassing booth.

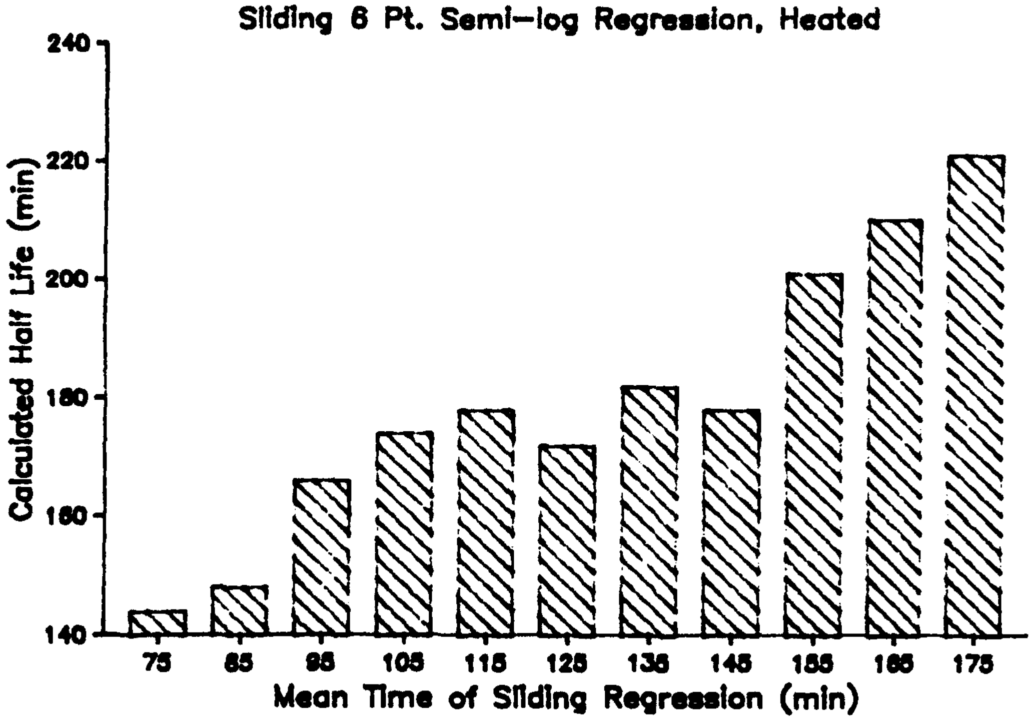

Figure 22. Vapor washout half-life for static OFGB1 (heated).

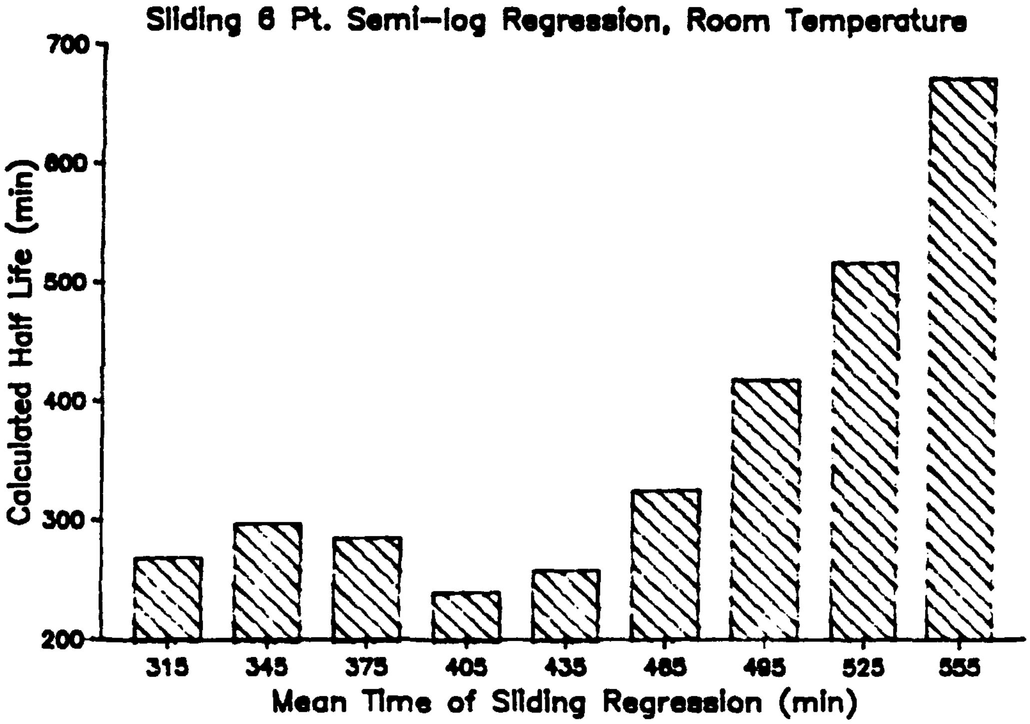

Figure 23. Vapor washout half-life for static OFGB3 (Ambient).

CONCLUSION

Rothe Development successfully completed construction and evaluation of a ventilated off-gassing booth. Replacement and/or modification of the existing nonventilated offgassing booths should be considered for future research and testing programs.

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2. Scott, W.R. Simpson R.E. Relationship between the amount of methyl salicylate offgassed by subjects in sealed booths and the measured booth vapor levels. USAFSAM-TP-89-3, Oct. 1989.